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GAS TURBINE COMBUSTION CHAMBERS WITH FILM EVAPORATION

by

A. W. Hussmann

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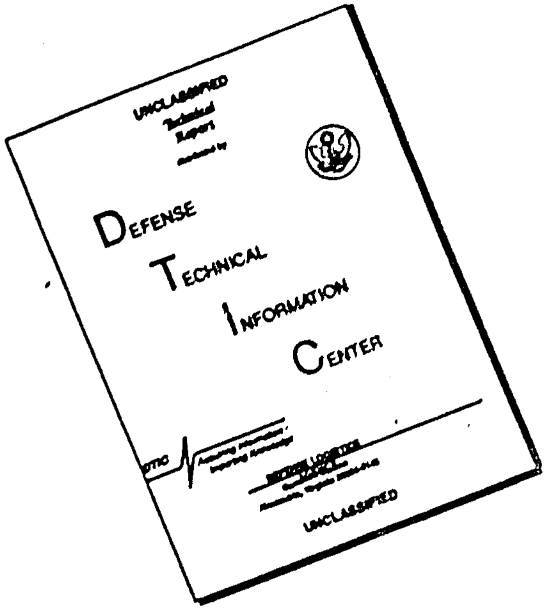

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ABSTRACT

The paper reports on an attempt to apply Meurer's film vaporization combustion method (M-method), originally developed for diesel motors, to the combustion chambers of gas turbines. (in the M-method, instead of distributing the fuel in the air, it is laid on the wall of the combustion chamber and evaporated, mixed, and fired by means of the appropriate movement of air — the evaporation rate, as a function of the air velocity, and gas and flame temperature, providing an additional control element for the combustion process.). The three points primarily considered in this report are: 1) The formation of a fuel film of sufficient surface extent on the wall. 2) The evaporation of the fuel from this wall and its molecular mixing with the combustion air at sufficiently low temperatures and delay times to minimize cracking. 3) The injection of the fuel-air mixture into a combustion zone in which oxidation reactions may first take place. The characteristics of the M-system are realized in a stationary evaporation tube having a connected reaction chamber: filming of the fuel, air eddy, and combustion in a powerful eddy field. Evaporation heat is derived through recirculation of combustion products from the reaction chamber into the evaporation zone; the intensity of this recirculation was measured by plotting the velocity profile on a series of configurations. Tests with several combustion chamber mockups (corresponding in size to an engine with a shaft power of 40 h.p.) indicated that operation with blue, smokeless, low-radiation flame is

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possible over a wide range of air conditions, combustion chamber pressures, and fuel types. Orig. art. has: 11 figures.

GAS TURBINE COMBUSTION CHAMBERS WITH FILM EVAPORATION

A. W. Hussmann

Abstract

Observations that were made in recent years on the combustion in diesel engines underwent a basic change in the wall application of fuel as introduced by Meurer (M-method of M.A.N.). Instead of the fuel being distributed in the air it is at first applied to the wall and then vaporized by a suitable air movement, mixed and then fired. The vaporization speed which is again a function of the air velocity and gas and flame temperature, represents an additional control possibility in the combustion process.

The investigations that are to be reported in this article, represent an attempt to apply the M-method in diesel engines to gas turbine combustion chambers. The characteristics of the M-method are realized in a stationary vaporization tube equipped with a connecting reaction chamber: film-application of the fuel, air vortex, combustion process in a strong vortex field. The heat vaporization is obtained by means of recirculation of the combustion products from the reaction chamber in the vaporization zone. The intensity of this recirculation was measured by measuring the velocity profile in a series of configurations.

Tests with several model combustion chambers (the size of which correspond to an engine with a crankshaft performance of about 40 hp) show that operation with a blue, smoke-free and radiation poor flame is possible over a wide range of air ratios, combustion chamber pressures and fuels.

The opinion regarding the nature and the significance of the mixture formation processes for combustion in fast running diesel engines have changed basically in recent years. Meurer was responsible for this by discovering and developing the MAN-M-method. Meurer was correct when he spoke of an initial period in the introduction of the mixture formation in which the fuel is "introduced to the air" by vaporization and distributing it as homogeneously as possible and a second period in which the "air is brought to the fuel" [1]. The same holds true for the most part also in gas turbine combustion inasmuch as the "fuel is brought to the air" by means of vaporization and distribution accompanied by the same undesirable results on the velocity of a combustion and the soot formation.

The results that were obtained with the M-method at the Pennsylvania State University in the USA gave us the impetus to apply the M-method to gas turbine combustion chambers. Dr. Günter Maybach, the son of Karl Maybach, who unfortunately passed away so soon, worked on the first phase of the project as a doctoral thesis. His work was published as a doctoral thesis [2] and as a brief SAE-report [3].

Within the framework of this brief report the mixture formation and reaction kinetic performance will not be given in detail. Detailed reports by Meurer [4] and others are available including a doctoral thesis by Zimmer [5] at the Institute of Professor Jante at the Polytechnical Institute Dresden. I would like to deal here in the consequences which we obtain from these presentations which, at that time, had not as yet been worked out as clearly. This includes the following points that are primarily considered in this report:

1. The formation of a fuel film of sufficient surface on a wall.

2. The evaporation of the fuel from this wall and its molecular mixing with the combustion air under sufficiently low temperatures and delay times in order to minimize cracking reactions as much as possible.

3. Supplying the fuel-air-mixture in a combustion zone in which the oxidation reaction then takes place.

The prevention of the fuel decomposition prior to oxidation which was mentioned in number 2 above is very important in order to prevent the formation of soot and for slow combustion, that is, the appearance of yellow flames. I shall omit the study on the type of fuel supply and the film propogation on which Maybach [6] has already reported. After several preliminary tests we came to the solution that vaporization takes place the best in a tube through which very rough air flows. In so doing, we have already taken the wall application and the air turbulence from the M-method. Of course, the turbulent air provides another function to the M-engine in which the air speed as required for vaporization and the thermal mixing effect is attained for combustion in the centrifugal field by means of the turbulence. The turbulent field also satisfies the additional function by means of recirculation in the vortex core. The heat that is necessary for evaporation is obtained from the combustion zone in the vaporization zone.

This is made clearer in the schematic drawing shown in Fig. 1 of the first combustion chamber test stand. This test stand corresponds to the conventional design in which the air flow is divided into a primary portion which is used primarily for turbulence, mixing, and combusting the fuel-air mixture; into a secondary portion which again unites with the main portion in the flame tube and is used primarily to keep the exhaust gas temperature of the turbine within tolerable limits.

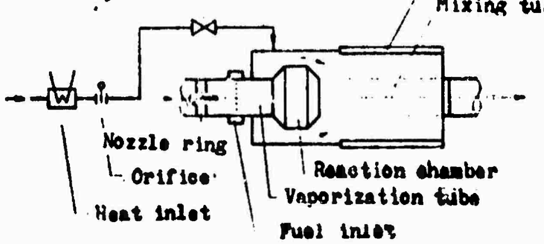

Fig. 1. Schematic drawing of the first combustion chamber test stand.

From the schematic drawing in Fig. 1, we can see that the primary portion flows through a nozzle ring which produces the turbulence and then into the vaporization tube. The fuel is introduced into the vaporization tube under slight overpressure behind the nozzle ring through radial holes. The incoming velocity of the fuel is kept so low, so that vaporization does not take place but rather that the fuel is spread by the air in spiral paths on the wall of the tube in the form of film strips. In order to join the individual strips in an unbroken film, a minimum number of openings are necessary which, in our case, amounted to about 8. In most tests, 24 to 32 openings were used.

In order to prevent the fuel from cracking, as was already mentioned above, the vaporization zone was separated from the combustion zone as suggested by Doctor Maybach. In Fig. 1, therefore, the vaporization tube follows the "reaction chamber" in which the main portion of the combustion takes place and in the latter there is a sudden expansion and then a renewed constriction of the flow cross section. The reaction chamber opens up into a flame tube in which the secondary air flows through holes where it mixes with the combustion gases. We only found out later that this flame tube is superfluous and that the mixture of both air currents can take place in the space that is formed by the tube shaped observation window. The omission of the flame tube has an additional advantage in that the flame can be observed through the window without hinderance. The mixing tube is followed by a cooling zone, which is not shown in the figure above, which can be regulated by means of water injection and by a butterfly valve through which the pressure

level can be controlled in the combustion chamber. Nevertheless, there was a variable restriction in the secondary flow by means of which the ratio of the primary to the secondary air could be changed.

The reaction chamber is connected to the vaporization tube. It was found, however, that it was necessary to isolate the reaction chamber from the vaporization tube in order to prevent heat being conducted to the vaporization tube. When the vaporization tube became too hot cracking of the fuel took place which was connected with yellow flames, soot and deposits in the vaporization tube.

This first test stand still corresponded to the presentations of a conventional combustion chamber in the primary and secondary flow each of which flow parallel through the throttle point which is formed by a light sheet metal which causes the turbulence in the primary portion and the inlet opening in the flame tube in order to mix the secondary portion with the combustion gases. By means of the mutual separation of this throttle section, the ratio of both of the partial flows is regulated.

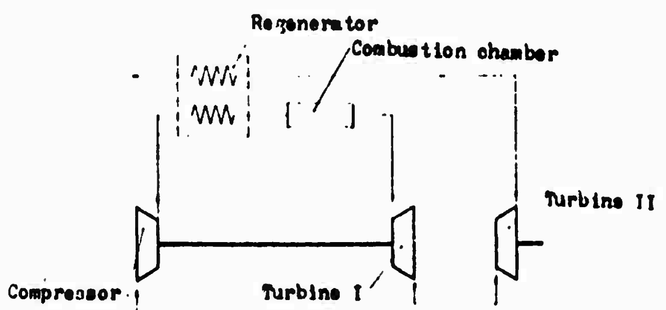

Fig. 2. Schematic drawing of a conventional gas turbine engine and heat recovery.

A schematic of a conventional gas turbine engine is shown in Fig. 2 which will correspond to the combustion chamber test stand shown in Fig. 1. As will be shown later, it can be seen that in the film vaporization combustion chamber only a little more than a stoichiometric air mixture (λ = 1 to 1.5) needs to flow through the vaporization tube. In engines with heat recovery we must, however,

work with quite a high total ratio of λ in order to keep the turbine inlet temperature within tolerable limits. Even in the case of full load and acceleration, the air ratio must not be less than about from 5 to 6, whereas in the partial throttle areas it can drop to about 15. By means of the vaporization tube with its pressure loss that is necessary in order to produce the turbulence only a small portion of the total air need only flow through it.

It is obvious, as is shown in Fig. 3, only to allow the secondary portion to flow through the regenerator. In so doing, the throttle losses in the turbulent producer and the pressure losses which are necessary for the heat exchanger, must be connected parallel and the entire pressure loss is reduced considerably.

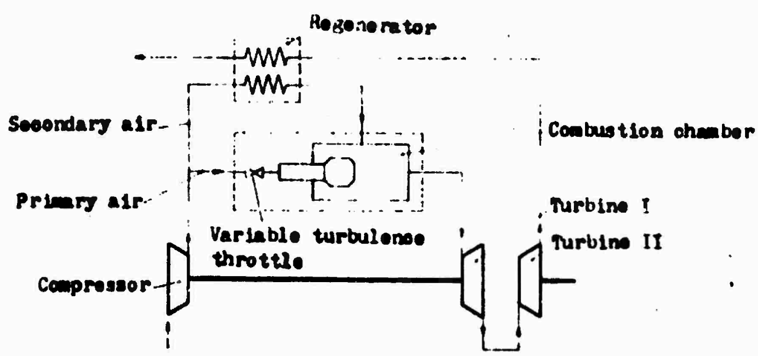

Fig. 3. Schematic drawing of a gas turbine engine with film vaporization combustion chamber and heat recovery only in the secondary air flow.

Naturally, we could also basically imagine a circuit such as this for conventional combustion chambers. This is not possible from a practical point of view because in a conventional flame tube combustion and mixing is connected with secondary air. In the proposed film evaporation with the subsequent reactor chamber the combustion is essentially limited to the reactor chamber and the mixing can take place with secondary air without essential loss in pressure and independently of the combustion.

The second combustion chamber test stand which corresponded to an arrangement of this type, is shown schematically in Fig. 4. The

primary and secondary air flow can be regulated and measured separately in this installation. The heat exchanger and the regulator valve make it possible to monitor the temperature increase and the pressure loss in the regenerator. In contrast to the first test stand in which a nozzle ring is used as a turbulence generator, the primary air flows through a controllable tangential inlet slot in the vaporization tube. In Fig. 4 it is also shown that the vaporization tube is not cylindrical along its entire length but rather a portion of it is conical in order to increase the recirculation from the reactor chamber as will be discussed.

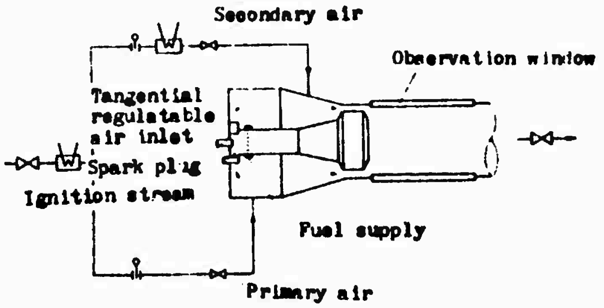

Fig. 4. Schematic drawing of the second combustion chamber test stand.

The separation of vaporization, mixing, and combustion is possible only when the heat that is required for vaporization is returned by recirculation from the combustion zone. This was made possible by utilizing the negative pressure that is generated in the vortex core in comparison to the pressure on the output of the reaction chamber by means of which the secondary flow allows a strong recirculation flow from the reaction chamber to be attained in the vaporization tube. In Fig. 5 we see schematically the flow components in a plane through the tube axis. The size of this recirculation flow can obviously be influenced by the layout of the inlet slit, the length and conicity of the vaporization tube an. the geometry of the reaction chamber. As was indicated, a real flux of secondary air in the reaction chamber as well as air and combustion gases from the reaction chamber take place in the vaporization tube. In order to conceive the magnitude of the recirculation three measuring planes A, B and C in connection with a specific configuration are given of

the throughput rate that was measured in a flow model. These values hold true without combustion. Accordingly, in connection with a 100% total throughput the reflux in the reaction chamber is 120%, in the vaporization tube (B) it is 70% and even at the beginning of the vaporization tube (C) in the vicinity of the fuel supply it is still 9%. After combustion takes place these values are, naturally, reduced. This strong negative flow of mass which again reverses and must flow in a positive direction not only has the effect of the secondary air to take part in the combustion and to bring heat into the vaporization tube, but it also has the desired effect of producing a radial exchange component and increases the turbulence. Also the still unclear relationship between the velocity profiles, turbulence and vaporization in a crooked flow cannot be delt with in detail here.

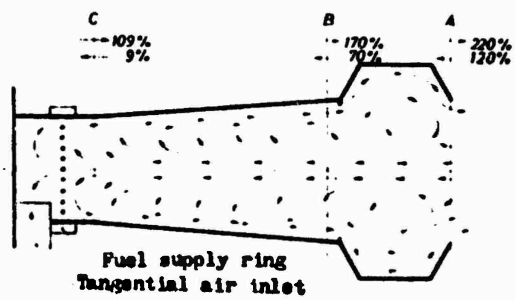

Fig. 5. Schematic drawing of the velocity components in an axial plane.

The tangential components of the velocity that were measured with a hot wire are shown in Fig. 6. These measurements were made on a model of a somewhat larger diameter than the combustion chamber shown in Fig. 1. The counter pressure was atmospheric and the difference pressure, i.e., the velocity, was suitably selected for the test conditions. It was tolerable as was proven by comparative investigations over a wide velocity range, that the velocity profile and consequently the recirculation assistance were independent of the absolute velocity as was expected.

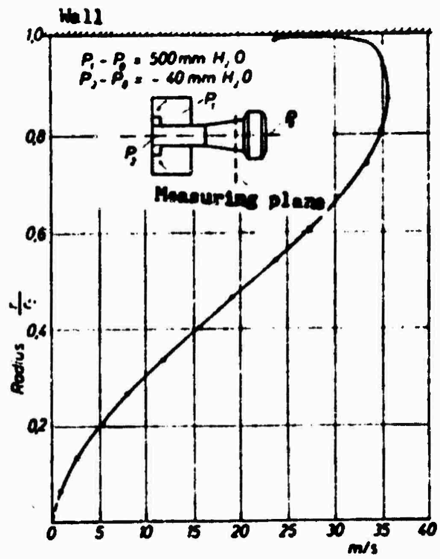

Fig. 6 Tangential velocity measuring plane 25 mm in front of the reaction chamber 2.5"Ø×8" length; 6"-5° cone, 5"Ø reaction chamber, 3"Ø outlet.

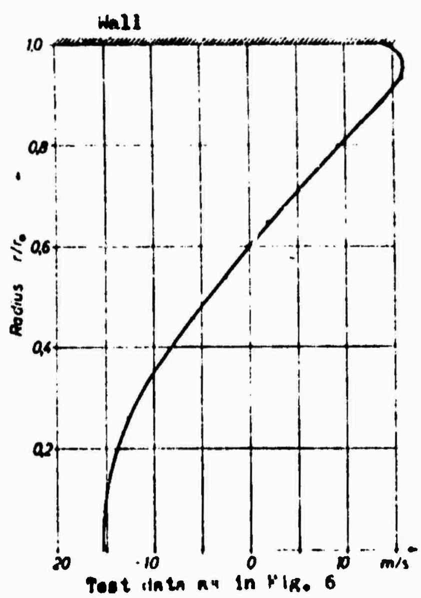

Fig. 7. Axial velocity.

The velocity profile shows a form which is a solid body turbulence except in the outer zone. This form can, naturally, be manipulated somewhat by the form and the direction of the inlet slot. In this way it is possible, for example, to move the velocity maximum more toward the axis. In so doing, the recirculation assistance becomes smaller but interestingly the penetration depth in the vaporization is greater.

The accompanying axial components of the velocity are shown in Fig. 7. We can see that the reflux in a tube core of about 60% of the radius with about the same velocity as the outwardly directed flow results. In order to make a comparison of the mass flow ratio possible the same axial velocities are presented in Fig. 8 over the square of the radius in connection with which the surfaces under the curve are then to be considered as the mass flow. The recirculation from the reactor chamber in the vaporization chamber, thus, amounts to 71% here.

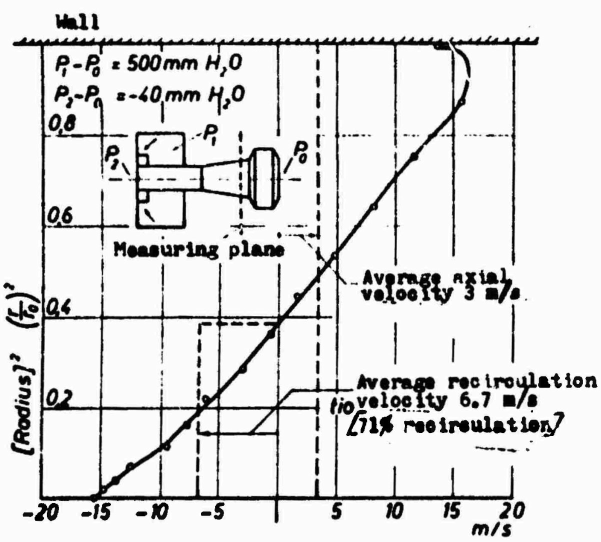

Fig. 8. Axial velocity (mass flow) (25 mm in front of the reaction chamber) 2.5"Ø×8" length; 6"-5° cone, 5"Ø reaction chamber, 3"Ø outlet.

The extent to which the recirculation is influenced by the conicity and by the size of the inlet slot is shown in Fig. 9. In this case, for example, the recirculation in a conical tube decreased from 76% to 26% by increasing the tangential inlet slot by four times. In the cylindrical tube the corresponding values only amounted to 29 and 19%. All of these flow tests were conducted in a model with air at room temperature and atmospheric counter pressure. The velocity profile and recirculation ratios will certainly change in the combustion operation quantitatively; however, there is a tendency to remain equal.

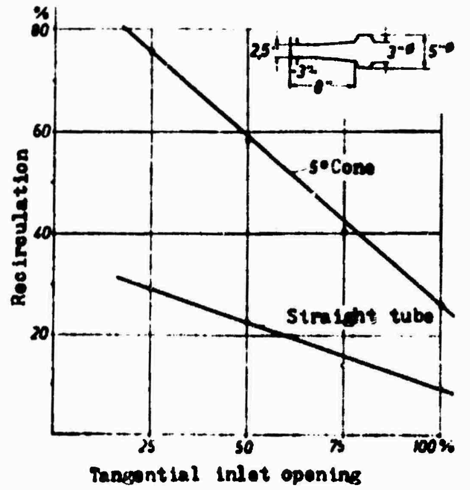

Fig. 9. Recirculation from the reaction chamber.

The combustion chamber tests were at first conducted with the combustion chamber shown in Fig. 1 in which, unfortunately, only the total throughput could be measured and by throttling the secondary air the ratio of the primary to the secondary air could be changed. Basically it was shown even in the first tests that it was possible to operate with a blue flame over a satisfactorily wide range of air ratios. In Fig. 10 pressure losses and efficiencies for two throttling positions in the secondary air flow are shown with a pressure in a combustion chamber of 2 ata. The efficiency was attained by means of very careful temperature measurements and with the use of straightening blades and estimating the heat losses. The efficiency is satisfactory and it is noteworthy that they remain equally high over all air ratios. It was, therefore, not shown how an optimum and a corresponding decrease in the efficiency for large and small air ratios is obtained in combustion chambers with fuel vaporization.

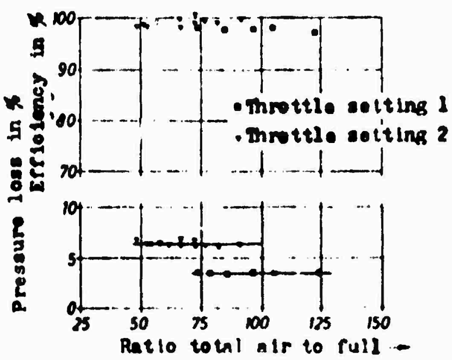

Fig. 10. Efficiency and pressure loss (combustion chamber) air throughput 0.157 kg/s, pressure 1.05 ata, inlet temperature 177°C.

On the second test stand the primary and secondary air could be measured separately and the amount of the primary air could be changed by means of a variable tangential opening with constant throttle in the secondary flow (regenerator). It was, thus, shown that for the operating limits of the combustion chamber the primary air ratio only is of importance and that, thus, there is no "poor" boundary to define as the primary air:fuel ratio in connection with the "blow-out" inlet.

The boundaries of the blue flame in the second test stand with variable, tangential air inlet and cylindrical vaporization tube are shown in Fig. 11. Unfortunately, pressures and inlet temperatures are comparatively low which was due to test stand conditions. Higher inlet temperatures expand the range of the blue flame; higher pressures, on the other hand, reduce it as is understandable. By means of tests within the framework of the possible changes this tendency was established.

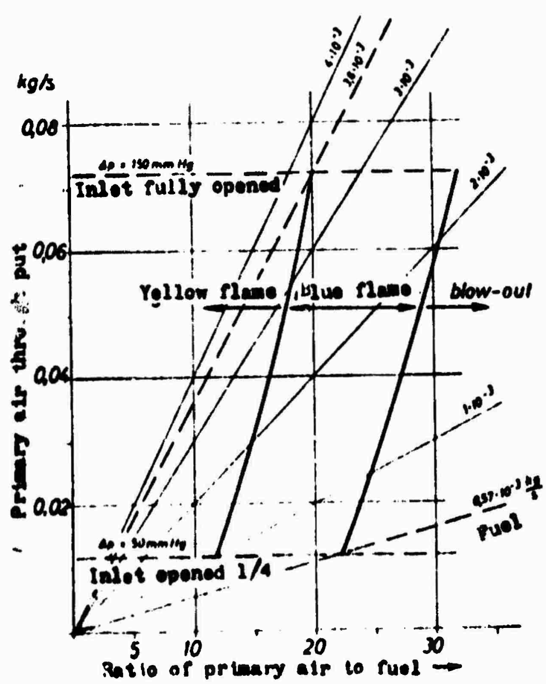

Fig. 11. Flame limits in the combustion chamber of the cylindrical vaporization tube 440×63 mm, pressure 3.3 ata; inlet temperature 200°C, diesel fuel.

In the selected limits of the pressure difference between inlet and mixing chamber of from 50 to 150 mm Hg and a variation of the inlet opening of from 1 to 4, operation with a blue flame could be obtained even when diesel fuel was burned over the range of fuel and primary air throughput of from 1 to 6 each. In order to maintain operation of this type with a blue flame, it is necessary to couple the fuel flow and the primary air-inlet opening.

The insensitivity to fuel quality could be determined by the character of the film vaporization.

Operation with a blue flame was possible up to a pressure of 3.5 ata with JP4, JP5, heating fuel and with standard diesel fuel. The flame limits that are shown in Fig. 11, for example, were determined with diesel fuel. The exhaust gas in each case fell in the blue flame range without any visible or measurable soot and deposits were not present in the vaporization tube, reaction chamber, and mixing tube. It was preassumed, of course, that the combustion air was preheated to a temperature which corresponded somewhat to that of the compressor.

The fact that the vaporization heat originated exclusively from the recirculated combustion gases was proven indirectly in two ways. If the engine was operated with preheated primary air but with cold secondary air (room temperature) vaporization was slight. It was then clearly visible how liquid fuel entered the reaction chamber and how it burned incompletely in long yellow flame lines. As was proven in the flow tests, secondary air passed through the reaction chamber to the vaporization tube whereby the temperatures with cold secondary air could be too low. On the other hand, it could be proven that by heating the vaporization tube wall with electricity to a temperature of about 300°C the flame limits were hardly influenced.

Since the combustion is limited to a very small range and no long flames are required the energy conversion per unit design volume and pressure unit is quite large. For the combustion chamber shown in Fig. 1 with a total air ratio of 50, a combustion chamber load of,

for example, $90 \cdot 10^6$ kcal/m^3h·at, was measured the volume of which included the entire vaporization zone, reaction chamber and flame tube zone.

The tests that are described in this article have proven that basically converting the M-method of diesel engines to gas turbine combustion chambers is possible. An essential advantage was shown in the fact that combustion with a blue flame in a wide range and with various fuels, including diesel fuel, was possible. In so doing, soot, strong radiation and deposits could be completely eliminated. It is expected that with still higher combustion chamber pressures operation with a completely blue flame is no longer attainable but that the advantages of flame vaporization that are described are maintained for the most part. The tests that are described in this article were limited by the given laboratory conditions with regard to pressure and air temperatures and, of course, an entire series of questions remained unanswered.

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